Health Impacts of Climate Change and Ozone Depletion: An Ecoepidemiologic Modeling Approach

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Anthropogenic climate changes and stratospheric ozone depletion affect human health in various ways. Current mainstream epidemiologic research methods do not appear well adapted to analyze these health impacts, which involve complex systems influenced by human interventions or simpler processes that will take place in the future. This paper discusses a different paradigm for studying the health impacts of global environmental changes and focuses on the development of integrated ecoepidemiologic models using three examples—the effect of climate change on vector-borne diseases, the effect of climate change on thermal-related mortality, and the effects of increasing ultraviolet levels because of ozone depletion on the rates of skin cancer. — *Environ Health Perspect* 106(Suppl 1):241–251 (1998). *http://ehpnet1.niehs.nih.gov/doc/1998/Suppl-1/241-251martens/abstract.html*

Key words: climate change, ozone depletion, health impact, integrated models, ecoepidemiology

Introduction

The health of a population, if it is to be maintained in a sustainable state (*1*), requires clean air, safe water, adequate food, tolerable temperature, stable climate, protection from solar ultraviolet (UV) radiation, and high levels of biodiversity. Socioeconomic changes and health interventions have improved population health in recent decades, although there still are many disparities in fulfilled health potential on the global level, and amenable morbidity and premature mortality continue to exist (*2*). However, as a counter effect of economic development, health impairments are now occurring as the result of deteriorating global environmental conditions.

Major global environmental changes significantly affecting health include climate change and ozone depletion, and there is an increasing awareness of the possible consequences of these changes on human health (*3–8*). Because of these environmental changes, there is a need for a more comprehensive, quantitative evaluation of the impact of global climatic changes and stratospheric ozone depletion on human health. These changes constitute, on aggregate, a more fundamental hazard to human health than any that have occurred before and present major scientific challenges both conceptually and technically in the assessment of these health impacts. Central to this challenge to public health science is the need to move from reliance on empirical data describing the past to the use of anticipatory thinking and the mathematical modeling of potential future impacts. A major task for public health science is to provide policymakers and their constituency with a clearer description of the anticipated future health impacts of global environmental change. New techniques and approaches will be needed to deal with the substantial uncertainties that inevitably surround these estimates.

This paper, which is based on Martens (*9*), addresses the assessment and evaluation of the impact on health of climate change and ozone depletion. Because mainstream epidemiologic methods often are not well adapted to the analysis of disease causation, which involves complex systems influenced by human interventions or more simple processes which will take place in the (distant) future, an ecoepidemiologic paradigm is advocated in the analysis of these complex environmental health relationships. Three examples—*a*) effects of climate change on vector-borne diseases and *b*) thermal-related mortality, and *c*) effects on skin cancer rates of increasing UV levels due to ozone depletion on skin cancer rates—illustrate the use of ecoepidemiologic models in the health impact assessment of global environmental change.

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Abbreviations used: GCM, general circulation model; MSC, melanoma skin cancer; UV, ultraviolet.

Health Impacts of Climate Change and Ozone Depletion

Broadly speaking, potential health effects of global climate change upon human health can be divided into direct and indirect effects, according to whether they occur predominantly through the impacts of climate variables upon human biology or are mediated by climate-induced changes in other biological and biogeochemical systems. Figure 1 summarizes important potential effects of climate change and ozone depletion upon human health.

In healthy individuals, an efficient regulatory heat system enables the body to cope effectively with thermal stress. Temperatures exceeding comfortable limits, in both the cold and warm range, substantially increase the risk of (predominantly cardiopulmonary) illness and deaths. Directly, an increase in mean summer and winter temperatures would mean a shift of these thermal-related diseases and deaths. Increased frequency or severity of heat waves will also have a strong impact on these diseases. If extreme weather events (droughts, floods, storms, etc.) were to occur more frequently, increases in rates of deaths, injury, infectious disease, and psychological disorder would result.

A major indirect impact of global climate change upon human health could occur through effects on cereal crop production. Cereal grains account for about two-thirds of all foodstuffs consumed by humans. This impact would occur through the effects of variations in temperature and moisture upon germination, growth, and photosynthesis, as well as indirect effects upon plant diseases, predator–pest relationships, and supplies of irrigation water. Although not a certainty, it is likely that tropical regions will be adversely affected (*10*), and in such increasingly populous and often poor countries, any apparent decline in agricultural productivity during the next century could have significant public health consequences. Another possible indirect effect on human health is a change in the transmission of vector-borne

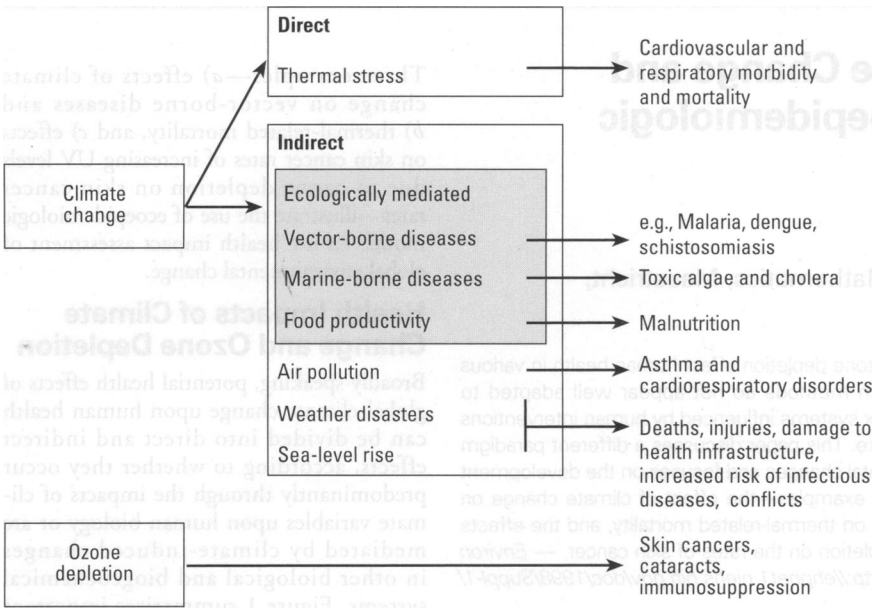

Figure 1. Health impacts attributable to climatic changes and ozone layer depletion. Data from Patz and Balbus (*16*).

diseases (*11*). Temperature and precipitation changes might influence the behavior and geographic distribution of vectors and thus change the incidence of vector-borne diseases, which are major causes of morbidity and mortality in most tropical countries. Increases in non-vector-borne infectious diseases, such as cholera, salmonellosis, and other food- and water-related infectious diseases could also occur, particularly in tropical and subtropical regions, because of climatic impacts on water distribution, temperature, and the proliferation of microorganisms.

Many health impacts could also result from deterioration in physical, social, and economic circumstances caused by rising sea levels, climate-related shortages of natural resources (e.g., fresh water), and impacts of climate change on population mobility and settlement. Conflicts may arise over decreasing environmental resources. The climate change process is associated with air pollution, since fossil fuel combustion produces various air pollutants. Furthermore, higher temperatures would enhance the production of various secondary air pollutants (e.g., ozone and particulates). As a consequence, there would be an increase in the frequency of allergic and cardiorespiratory disorders and deaths caused by these air pollutants.

If a long-term increase of UV-B radiation due to stratospheric ozone depletion occurs, melanoma and nonmelanoma skin cancer will increase with people having lightly pigmented skins being most susceptible. The incidence of various diseases of the eye, particularly pterygium and cataract, is also likely to increase. There is less certainty about whether damage to the human immune system (both local and systemic) will occur. This could lead to increased vulnerability to infectious diseases. A potentially more important indirect effect of increased UV-B levels reaching the Earth could be the UV-B-induced impairment of photosynthesis on land (food crops) and in the sea (phytoplankton), which would reduce the world's food production.

Many uncertainties remain, however, not only regarding these health impacts but also related to scenarios of climate change and ozone depletion. Table 1 summarizes the present knowledge and uncertainties related to the health impacts discussed above.

Conventional Epidemiology versus Ecoepidemiology

Environmental epidemiology generally refers to the influence on human health of environmental factors that are outside the immediate control of the individual (*12*). Exposures of interest to environmental epidemiologists include air pollution, water pollution, and occupational exposure to physical and chemical agents. The formal study of the risks associated with these health hazards has contributed much to the evolution of modern quantitative epidemiologic research methods. The risks to health are in general easily understood because they entail obvious causal effects, linear (or otherwise orderly) relationships, and act by direct toxicologic insult to organ systems or metabolic pathways. Conventional (environmental) epidemiologic research thus relies on empirical data that describe past real-world experiences of human populations; the risks to health associated with specified factors are then estimated by comparing rates or proportions or by fitting statistical models to the data.

By contrast, most effects of climate change and ozone depletion would not result from the familiar toxicologic mechanisms that mediate the effects of localized exposure to environmental pollutants. Rather, they would arise from more complex processes that result from disturbances of natural global biogeochemical cycles, and the scale of these effects would apply primarily to populations or communities rather than to individuals, for whom a risk is increased slightly, but remains small.

Furthermore, assessment of the future impacts of global environmental changes concerns the potential effects of an anticipated exposure, i.e., assessment of future (scenario-based) possibilities rather than estimation of risks based on past realities. The key point is that there is a fundamental difference between a data-based, explanatory approach and a scenario-based, descriptive approach. The latter uses existing information about climate and UV-related factors, such as infectious agents and skin-cancer rates to project how a change in such factors would affect populations.

Some health impacts of global environmental change can be estimated by reasonable extrapolation of relatively simple cause–effect models. For example, a change in ambient temperature is expected to change the number of thermal-related deaths. However, this may not be appropriate if the health risk concerned is linked to an ecologic phenomenon or entity such as the impact on vector-borne diseases. Furthermore, climate change and ozone depletion would not affect human health in isolation, but simultaneously and in conjunction with other ecological and demographic changes. Therefore, the net impact of global environmental changes would depend on various interactive phenomena, e.g., multiplicative exposure effects, feedback pathways, and differences in the vulnerability of (local) populations.

Three major polarities appear to characterize this new research domain compared to conventional epidemiology:

Table 1. Summary of known effects and uncertainties regarding health impacts of climate change and ozone depletion.

Health effect	Known effects	Uncertainties
Thermal stress	Mortality (especially cardiopulmonary) increases with cold and warm temperatures Older age groups and people with underlying organic diseases are particularly vulnerable Mortality increases sharply during heat waves	The balance between cold- and heat-related mortality changes The extent to which heat waves affect morbidity of terminal patients The role of acclimatization of people to warmer climates
Vector-borne diseases	Climate conditions (particularly temperature) necessary for some vectors to thrive and for the microorganisms to multiply within the vectors are relatively well known	Indirect effects of climate change on vector-borne diseases such as changes in vegetation, agriculture, sea-level rise, migration, etc. Effects of socioeconomic development, resistance development, etc.
Water/food borne diseases	Survival of disease organisms (and insects that may spread them) is related to temperature Waterborne diseases most likely to occur in communities with poor water supply and sanitation Climate conditions affect water availability Increased rainfall affects transport of disease organisms	For many organisms the exact ambient conditions at which they survive and are transmitted are not known Interaction with malnutrition is not well understood
Food production	Temperature, precipitation, solar radiation, and CO_2 are important for crop production Crop failure may lead to malnutrition Undernourishment may increase susceptibility for infectious diseases	Variations in crop yield because of climate change are poorly understood Effects of climate on weeds, insects, and plant diseases are not well known Interaction between nutritional status and diseases is poorly understood
Skin cancer	Skin cancer incidence is related to UV exposure Aging increases the risk of skin cancer	Dose–response relationship between UV radiation and skin cancer, especially basal cell carcinoma and melanoma skin cancer is not completely clear
Cataracts	UV radiation damages the eye, more particularly the lens Different types of cataracts react differently to changes in UV radiation Etiology of cataracts is associated with age, diabetes, malnutrition, heavy smoking, hypertension, renal failure, high alcohol consumption, and excessive heat	Dose–response relationship between UV radiation and cataracts is not well known Interactions with other determinants of cataracts are not always clear
Immune suppression	UV suppresses immune systems in animal models and may adversely affect various infections In man, serial UV irradiation may cause proper immunization to fail UV-induced immunosuppression appears to be a risk factor for skin carcinomas	Interaction between immunosuppression and infectious disease incidence Effect of immunosuppression on vaccination efficacy

a) spatial scale, i.e., regional/global versus local impacts; *b*) temporal scale, i.e., future versus present health risks; and *c*) level of complexity, i.e., complex ecoepidemiologic processes versus straightforward cause–effect relationships. Current mainstream epidemiologic research methods do not appear well adapted to the analysis of disease causation, which involves complex systems influenced by human interventions or more simple processes that will take place in the future. Nor are the empirical sciences able to deal with uncertainties arising from such complex systems (*13–16*). So it appears that a different paradigm for studying the health impacts of global environmental changes is needed, one that would allow development of new approaches in the assessment of these health impacts. Here, this paradigm is labeled with the term ecoepidemiology; Table 2 summarizes the main differences between conventional epidemiology and an ecoepidemiologic framework, as discussed above.

The concept ecoepidemiology has been used by others, for example, to refer to the study of health impacts of chemical pollution of local/regional environments [e.g., work on the Great Lakes pollution, which affects fish and bird life, and indirectly humans (*17*)], or to the need to give better consideration to human disease origins in a social (human ecology) context (*18,19*). Here the term is used to refer to the health impact assessment of global environmental changes that should be able to take account of ecologic complexities and, at least as important, one that could be used to estimate future health risks, with maximum reference to existing epidemiologic knowledge of disease causation. (Epidemiologic studies provide many of the information building blocks for the ecoepidemiologic analysis.) Within ecoepidemiology most quantitative assessments will come from integrated mathematical computer modeling (*6,14,16*).

Integrated Assessment Modeling

Although mathematical modeling is often used by epidemiologists to gain insights into the observed dynamics of infectious disease epidemics, for example, or to estimate future time trends in diseases, the complex task of estimating future trends and outcomes in relation to global environmental change and human health requires

Table 2. Main differences between conventional epidemiology and ecoepidemiology.

Conventional epidemiology	Ecoepidemiology
Toxicologic	Ecologic
Estimation of risk from past realities	Assessment of future health risks
Short-time horizon	Long-time horizon
Estimation of more local risks	Estimation of global and regional risks
Statistical models	Mathematical models
Static cause-and-effect	System-dynamic, nonlinear models
Reductionistic approach	Holistic approach

the use of integrated, systems-based mathematical models (*14,20*). A systems approach is concerned with modeling real-world systems and studying their dynamics. Integrated modeling that builds on systems-oriented analyses concentrates on the interactions and feedback mechanisms between different subsystems of the cause–effect chain rather than focusing on each subsystem in isolation (*21*). Feedback processes can amplify or dampen important aspects of the system. For example, an important determinant of the number of people infected by malaria is the level of (temporary) immunity within the target population. Hence, in highly endemic regions with a high prevalence of immunity, the impact of a climate-related increase in the malaria transmission potential of the mosquito population will be lower—and will soon be counteracted by the further boost in immunity—than the impact in populations with initially low levels of immunity.

Because current knowledge is limited, only a partial integration is possible rather than a full, integrated assessment. In many cases, partial integrated assessment models strongly resemble a straightforward cause and effect approach or an interaction approach. In the cause and effect approach, it is assumed that other factors on the exposure unit are held constant—nonclimate factors, for example. The interaction approach, on the other hand, recognizes that climate, for example, is only one of a set of factors that influence or are influenced by the exposure unit (*22*), and the distinction is often difficult to make.

The major advantages of integrated assessment models (*23*) are *a*) the inclusion of systems in interactions and feedback mechanisms; *b*) the simplified nature of the modules in integrated models permit rapid prototyping of new concepts and exploration of their implications; *c*) uncertainties, crucial lacunae in current scientific knowledge, and weaknesses in discipline-oriented expert models can be identified and revealed; *d*) accumulation of uncertainties can be analyzed and interpreted; and *e*) integrated models are outstanding means of communication between scientists and exponents of many disciplines and between scientists and decision makers. Integrated assessment models do not pretend to offer comprehensive pictures of all relevant processes of complex realities; the interpretative and instructive value of these models, including the ones presented in the following sections, is far more important than their predictive potency, which is limited by the incomplete science on which they are constructed. Furthermore, integrated assessment models may serve as repositories of what is known about the elements of a system and their relationships and can augment extrapolation from historical data.

Obviously, integrated assessment models also have limitations and drawbacks. Following is a brief discussion of critical issues in using integrated systems-oriented models in the health impact assessment of global environmental change.

Aggregation Level. Assessment of health vulnerability due to stratospheric ozone depletion and climate change may be done on a variety of geographical scales that vary from a village to an entire country, region, or the world as a whole. Furthermore, the response time of human systems to environmental changes also differs between diseases and locations. For example, climatic changes simulated with general circulation models (GCMs) have relatively coarse spatial resolutions and grid cells of a few degrees but run at a fine temporal resolution; ecological models mostly require data of fine spatial resolution, but their time resolutions may vary from one day to a season or a year. In general, because of the multiple ecosystem levels that must be altered before human health is affected, there will be a time lag between the change in the environmental stressor and health impacts (with the exception of thermal-related mortality, which is a result of more direct disease processes) (*16*). Aggregation, therefore, is a critical issue in the design of the models, and which spatial and temporal level to chose depends on the model's purpose.

Validation. Validation may be defined as the procedure for testing the adequacy of a given mathematical model (*20*). One of the problems often encountered in applying system-based models in less-developed countries where many of the health impacts are likely to occur is that the models, often adequately validated in the data-rich developed world, are found to be ill suited to or poorly calibrated for use in less-developed countries. A paucity of data for validation generally means that data-demanding models often cannot be used in such circumstances, and one must rely on less data-demanding models (*22*). Unavailability or paucity of data will necessitate a reliance on simplified assumptions to generate an initial framework for analysis; this framework can be used to focus interdisciplinary communication on assessing health risks and to identify priorities for future research. Although the use of such assumptions and simplifications will potentially decrease the quantitative accuracy of the assessment, it should still allow adequate prioritization and estimation of relative risk (*16*). Also, it is difficult to validate the often highly aggregated global model outcomes. However, more confidence in model outcomes can be obtained by validating the model on a local or regional scale where data are at hand. An iterative cross-validation of large- and small-scale studies may be essential in the process of validating integrated assessment models (*24*).

Uncertainties. Projection of health impacts is contingent on a multi-layered infrastructure of uncertainties from other disciplines such as climatology, atmospheric chemistry, agricultural science, ecology, social sciences, economy, and so on. From those disciplines come projections about environmental changes (for example, temperature increase, ozone depletion rates). The degree of unpredictability of global environmental change processes and their impact upon human health introduces scientific uncertainties. These may be narrowed as a result of further scientific research or more detailed/appropriate modeling. Scientific uncertainties include, for example, incomplete knowledge about the dose–response relationships between UV radiation and skin cancer incidence. Social and economic uncertainties arise from the inherent unpredictability of future geopolitical, socioeconomic, demographic, and

technological evolution. Examples of social and economic uncertainties are the cultural adjustments in time that may have an impact on the relationship between thermal stress and mortality rates, for example, improvements in housing conditions and better clothing. Figure 2 illustrates the sequence of uncertainties introduced by the linkage of separate modules; in general, the uncertainty range widens as one moves to more remote links in the cause-and-effect chain (see also Figure 9). On the other hand, integrated assessment models enable comparison of the relative importance of these uncertainties (*14*).

Three Examples

The approach to assess the health risks of climate change and ozone depletion depends to a large extent on the problem being studied. The effect of climatic changes on vector-borne diseases is probably the clearest example of a health impact with complex climate-related, ecologically based dynamics. However, besides incorporating ecologic components (e.g., changes in vector distribution are linked with changes in vegetation patterns), the system dynamic models developed to assess climate impacts on vector-borne diseases, discussed below, are based on basic infectious disease epidemiology. In general, more straightforward health impacts, for example, the impact of changes in ambient temperature on mortality, can be studied using simple extrapolation of dose–response relationships. Furthermore, assessment of the mortality changes related to thermal stress as a result of a change in ambient temperature and the effects of increased UV-B radiation on skin cancer rates has a clear epidemiologic basis in that most of the input parameters are derived from epidemiologic studies.

Climate Change, Thermal Stress, and Mortality Changes. Estimations of the direct impacts of climate change on thermal-related illness and mortality can be generated by simple extrapolation of current temperature–mortality relationships. The example below considers the potential changes in numbers of deaths associated with warmth and moderate cold related to the gradual influences of climate changes on health risk. It does not consider the impact of periods of extreme heat and cold.

A summary of some selected studies on average temperature–cardiovascular mortality relationships is given in Figure 3. The relationship between mortality and temperature is visualized as a V-shaped function, with mortality rising not only at very high and low temperatures but also at more moderate temperatures (Figure 4). Data from epidemiologic studies on the relationship between temperature and mortality suggest that on aggregate a 1°C increase of monthly mean temperature may increase total, respiratory, and cardiovascular mortality by 1.4, 10.4, and 1.6%, respectively, if the temperature exceeds the comfort range (the temperature at which mortality is lowest). Below this comfort range, a 1°C increase may decrease mortality rates by 1.0, 3.8, and 4.1%, for total, respiratory, and cardiovascular diseases, respectively. However, for total and respiratory mortality the estimates are based on

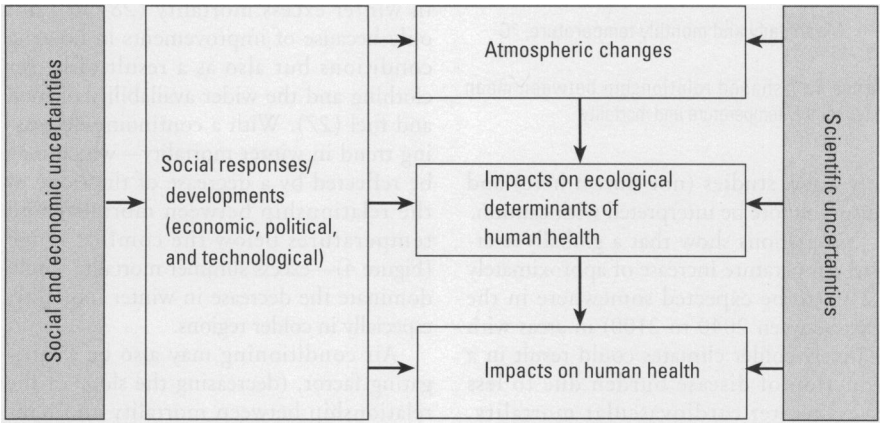

Figure 2. Layers of uncertainty underlying the health impact assessment of global atmospheric changes.

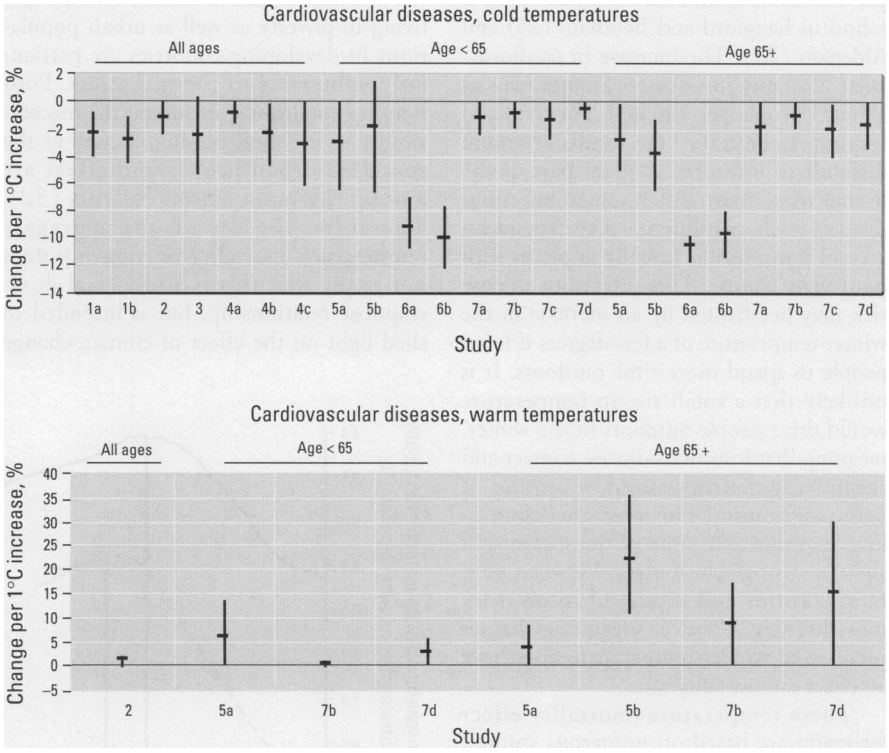

Figure 3. Change in cardiovascular mortality due to 1°C increase in average temperature (95% confidence interval). Study 1: Langford and Bentham (*25*); Study 2: Kunst et al. (*27*); Study 3: West and Lowe (*49*); Study 4: Sakamoto-Momiyama and Katayama (*50*); Study 5: Pan et al. (*51*); Study 6: Green et al. (*52*); Study 7: Bull and Morton (*53,54*); and Study 8: Shumway et al. (*55*). Cardiovascular mortality: 1a: coronary heart disease; 1b: cerebrovascular disease; 2: cardiovascular disease; 3: coronary heart disease; 4a–c: cerebrovascular disease (a: New York, b: Tokyo, c: London); 5a: coronary heart disease; 5b: cerebral infarction; 6a: coronary heart disease; 6b: cerebrovascular disease; 7a,b: myocardial infarction; 7c,d: cerebrovascular disease (a+c: England and Wales, b+d: New York).

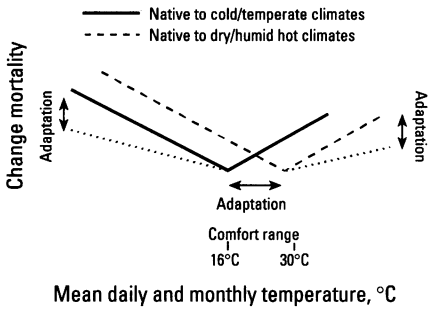

Figure 4. V-shaped relationship between mean daily/monthly temperature and mortality.

only a few studies (not shown here) and must therefore be interpreted with caution.

Simulations show that a globally averaged temperature increase of approximately 1.2°C (to be expected somewhere in the years between 2040 to 2100) in areas with relatively colder climates could result in a reduction of disease burden due to less excess winter cardiovascular mortality, especially among elderly people. Based on current mortality levels for selected regions (*9*), this decrease could be about 50 people per 100,000 population. A similar result is found in Langford and Bentham (*25*) and Alderson (*26*). The increase in cardiovascular mortality in warmer climates may be about 3 people per 100,000. For total and respiratory mortality the results are more difficult to interpret. A great part of the overall winter mortality is due to infectious diseases such as influenza that depend on aerosol transmission (usually in places with poor ventilation). This infectious disease risk may be affected by an increase in the winter temperature of a few degrees if it led people to spend more time outdoors. It is unlikely that a small rise in temperature would drive people outdoors in the winter, meaning that infectious disease contact and respiratory distress would be similar at both temperatures. However, after controlling for influenza, some of the studies still show a strong relationship between cold temperatures and total and respiratory mortality (e.g., *25,27*), suggesting that an increase in winter temperature does have an effect on mortality rates.

These temperature–mortality effect estimates are based on numerous studies, conducted mostly in developed, nontropical countries, some several decades ago. Part of the spread of the point estimates of individual studies reflects more than sampling variations, length-of-record problems, and other difficulties inherent in studies developed before masses of digital mortality and weather data were available. People may physiologically adapt to warmer temperatures, which may result in an increase of the comfortable temperature; furthermore, cultural adjustments over time may have an impact on the relationship between climate and mortality rates. In developed countries, socioeconomic progress over time has led to a reduction in winter excess mortality (*28–30*), not only because of improvements in housing conditions but also as a result of better clothing and the wider availability of food and fuel (*27*). With a continuing decreasing trend in winter mortality—which may be reflected by a decrease of the slope of the relationship between mortality and temperatures below the comfort range (Figure 4)—excess summer mortality would dominate the decrease in winter mortality, especially in colder regions.

Air conditioning may also be a mitigating factor, (decreasing the slope of the relationship between mortality and temperatures above the comfort range [Figure 4]), although this is much less likely to be a confounder in developing countries (*31*). There is also evidence that people living in poverty as well as urban populations in developing countries are particularly vulnerable to thermal stress. Poor housing conditions, including the inaccessibility to air conditioning, as well as the so-called urban heat island effect are among the main causes for this (*32*). Therefore, the use of one aggregate temperature–mortality relationship does not imply that this is a universal dose-response relationship, but is intended to shed light on the effect of climate change on the balance between cold- and warmth-related mortality changes.

The Impact of Ozone Depletion on Skin Cancer Incidence. Analysis of what happens with the tumor incidences in the course of time after the ozone layer changes is more complex than the previous example, due in particular to the relatively long incubation time between initial UV exposure and the first appearance of cancer. Although there is a large body of data, both experimental and epidemiologic, that confirms a causal relationship between accumulated UV dose and squamous cell carcinoma (*33,34*), the UV dose dependencies of basal cell carcinoma and melanoma skin cancer (MSC) (except for lentigo maligna melanoma) are less certain.

Earlier skin cancer assessments were based on comparison of two stationary situations (*35*) and did not include the delay between exposure and tumor development (*36*). The assessment model used here integrates dynamic aspects of the full source–risk chain: from production and emission of ozone-depleting substances, global stratospheric chlorine concentrations, local depletions of stratospheric ozone, resulting increases in UV-B levels, and finally, the effects on skin cancer rates (*37–39*). Figure 5 clearly shows the delay mechanisms in the effect of ozone depletion on skin cancer rates. Full compliance with the Copenhagen Amendments to the Montreal Protocol would lead to a peak in the atmospheric chlorine concentration around 1995, a peak in stratospheric chlorine concentration and ozone depletion around 2000, and a peak in skin cancer by

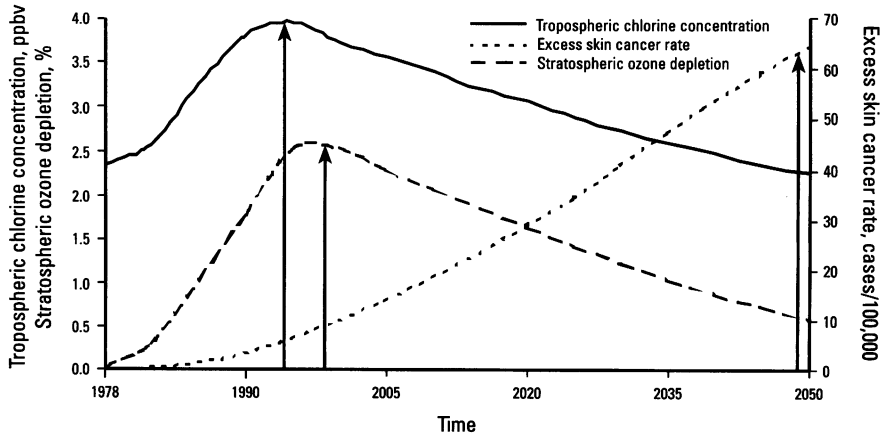

Figure 5. Delay mechanisms in the cause-and-effect chain with regard to the impact of stratospheric ozone depletion on skin cancer rates. Results are generated using the Copenhagen Amendments to the Montreal Protocol for squamous cell carcinoma skin cancer in Australia (*39*).

about 2050 (50 years after the peak in ozone depletion). The latter delay is mainly due to the fact that skin cancer incidences depend on cumulative UV-B exposure.

An important aspect in this modeling experiment is that skin cancer rates are very sensitive with respect to lifestyle (i.e., sun exposure habits). Changing lifestyles such as the trend toward sun worshipping during the last half century contribute greatly to the increases in the incidence of skin cancer. This has been identified as a serious public health problem in several western countries, and campaigns have been launched to curb excessive exposure to the sun. An increase in UV exposure of 50% would increase the excess number of skin cancer cases to 135% (Figure 6). Another factor contributing to a steady increase in the number of skin cancers is the aging of the population. Because older people build up a high cumulative UV dose during their lives, skin cancer occurs more frequently among the elderly. Figure 6 also shows that if a population is aging, the same level of UV exposure would lead to higher incidences of skin cancer than in a younger population, perhaps a 50 to 60% increase in the overall incidence. So it appears that in view of the several delay mechanisms involved in cancer onset and, additionally, the aging of the population, increases in incidences of skin cancer are likely to occur.

Climate Change and Vector-Borne Diseases. Vector-borne diseases are one of the most obvious examples of a category of health problems with complex, climate-related, ecologically based dynamics. Direct effects of the anticipated changes in global and regional temperature, precipitation, humidity, and wind patterns resulting from anthropogenic climate change are factors that have an impact on the vectors' reproduction, development rate, and longevity. In general, the rate of development of a parasite accelerates as the temperature rises. Indirect effects of climate change would include changes in vegetation and agricultural practices for example, irrigation. A further indirect effect of climate change would be associated with the rise in sea level and the resulting coastal flooding. Drought and desertification, including the migration or extension of global desert belts, could be expected to decrease vector-borne disease transmission. The influence that climate change is likely to exert on human populations may also play an important role in the dynamics of disease transmission. For example, the large-scale migration of populations from areas where vector-borne diseases are endemic into receptive areas (areas in which vector numbers and climate conditions are conducive to transmission) because of rural impoverishment, which is influenced by the dynamics of climate change (including the effects of sea level rise on low-lying coastal areas), would prove significant. Figure 7 summarizes the impact of a climate change on vector-borne disease transmission.

Simulations with vector-borne disease models (*40–42*) using climate change scenarios from three general circulation models combined with the epidemic potential index (which incorporates the basic dynamics of climatic influences on vector-borne disease transmission), show an increase of the populations at risk of malaria, dengue, and schistosomiasis (Figure 8), which are three of the world's most prevalent vector-borne diseases. It is estimated that 2400, 1800, and 600 million people presently are regarded to be at risk of contracting malaria, dengue, and schistosomiasis, respectively. If it is assumed that the population in the developing world will increase a total of approximately 8.6 billion by the year 2050, the additional number of people at risk because of anthropogenic climate change may increase about 720, 195, and 40 million people for these three diseases, respectively. In developed countries, there would be an increase in the risk of local transmission of these three vector-borne diseases associated with imported cases of the disease. However, given that effective control measures are economically

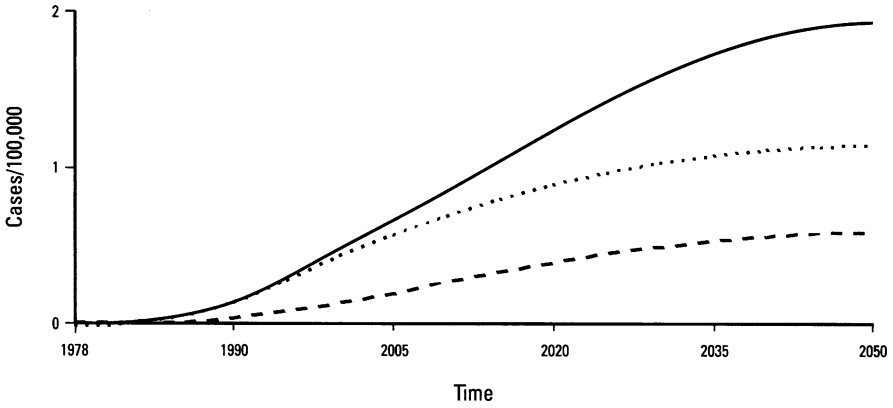

Figure 6. Excess squamous cell carcinoma skin cancer rates for Australia as simulated with the Copenhagen Amendments to the Montreal Protocol with a constant population scenario (dotted line) and an aging population scenario (straight line). The dashed line represents an aging population with a 50% decrease of UV exposure (*39*).

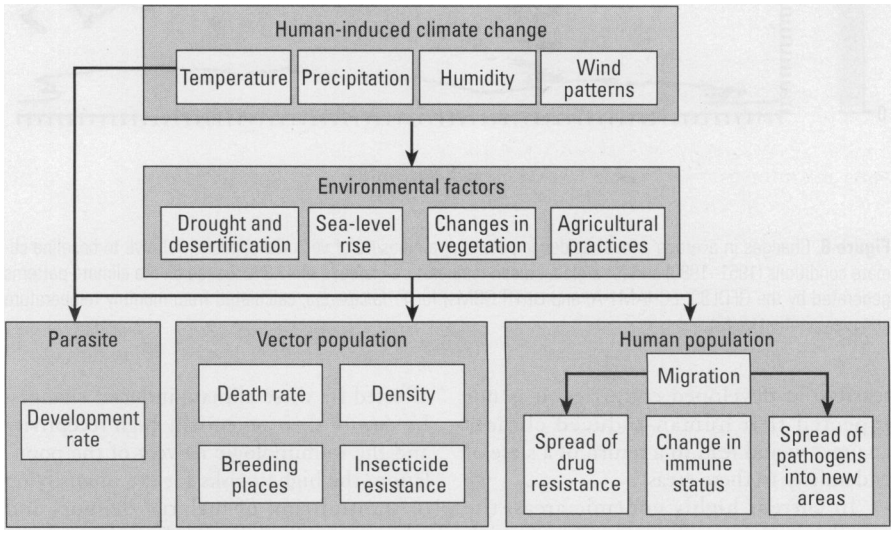

Figure 7. Schematic of the major climate-change implications for vector-borne diseases.

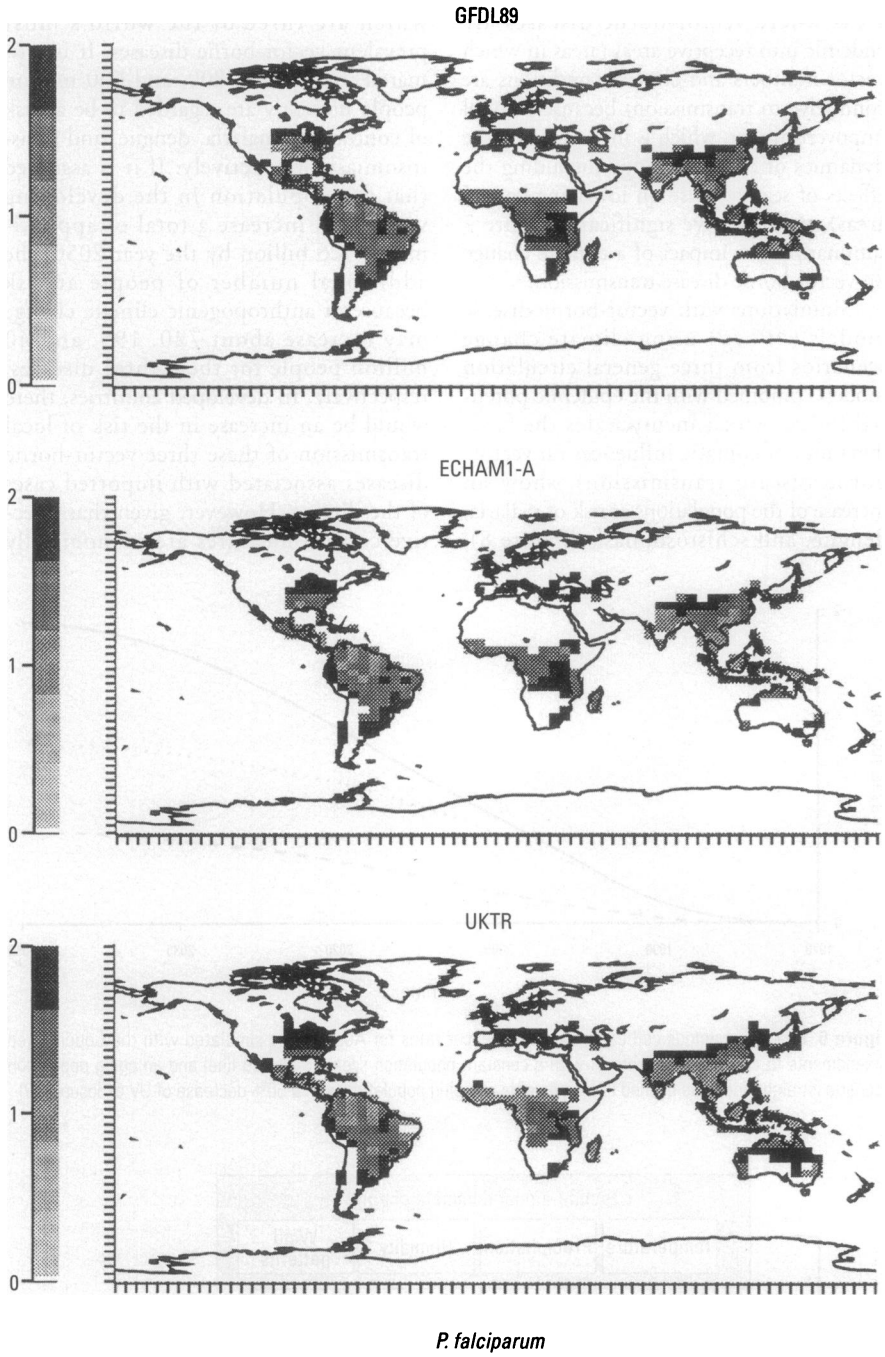

Figure 8. Changes in average annual epidemic potential, a measure of vectorial capacity, relative to baseline climate conditions (1951–1980) and for a global mean temperature increase of ~1.2°C (based on the climate patterns generated by the GFDL89, ECHAM1-A, and UKTR GCMs) for *P. falciparum*, calculated from monthly temperature and precipitation (*9,42*).

feasible in developed countries, it is not expected that human-induced climate changes would lead to a return of a state of endemicity in these areas.

In current highly endemic areas, the prevalence of infection is persistently high and probably will be only marginally affected by these climate-induced changes. In view of their potentially high receptivity and the immunologic naivety of the population, the highest risks for the intensifying of transmission of malaria, dengue, and schistosomiasis lie in the hitherto non- or low-endemic regions on the altitude and latitude fringes of disease transmission. Of particular importance is the increase in epidemic potential at higher altitudes within endemic areas such as the eastern highlands of Africa, the Andes region in South America, and the western mountainous region of China.

An important aspect of modeling climate change impacts on vector-borne diseases is the cumulation of uncertainties in the cause-and-effect chain: Uncertainties in the outcomes of climate change models influence the uncertainties in assessing a climate-related change in the transmission potential in a vector population; uncertainties in both the climate and vector models influence the uncertainties surrounding estimates of incidences of disease. Figure 9 illustrates the cumulation of uncertainties associated with climate change projections, malaria mosquito transmission dynamics, and malaria prevalence, based on variations of only some crucial parameters. This example, for *P. falciparum* in low-endemic regions, shows how the uncertainty range widens as one moves to more remote parts of the cause-and-effect chain. The change in malaria prevalence in the year 2050 may range between 1.8 and 2.5 times the 1990 level, based on a variation of only two of the model parameters in the human systems, whereas it may vary between 1.4 and 4.8 times the 1990 level if uncertainties in the climate and mosquito systems are also taken into account. Despite the large number of uncertainties, the general trend still indicates an increase in mosquito transmission dynamics and prevalence.

Discussion

The issues addressed in this paper demonstrate that global climate change and depletion of the ozone layer are likely to influence human health. Although some effects may be beneficial (e.g., in areas with relatively colder climates, an increase in ambient temperature could result in a decrease in cardiovascular mortality), most are expected to be adverse (e.g., increases in skin cancer rates and vector-borne disease incidence are to be expected). Some impacts would occur via direct mechanisms such as UV-related skin cancer and morbidity and mortality related to thermal stress; others would occur through indirect mechanisms such as transmission of vector-borne diseases.

With respect to the models described in this paper, the first point to make is that aggregating data about the natural world, including human populations, necessarily

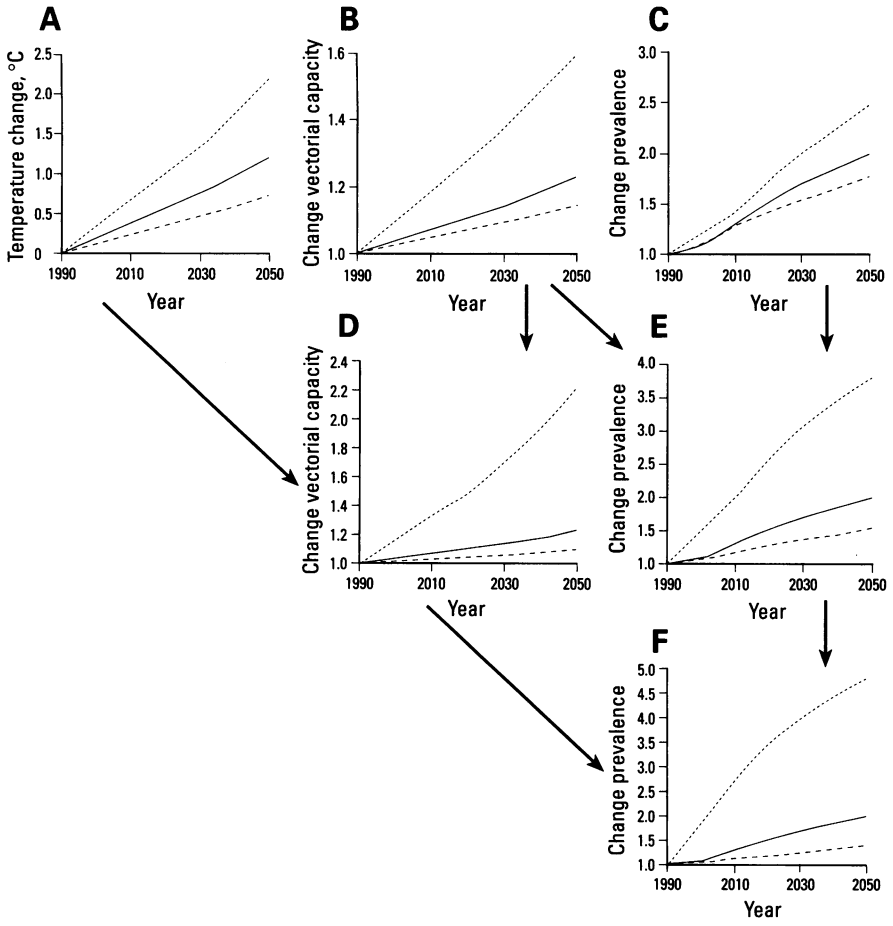

Figure 9. Cumulated uncertainties in modeling the impacts of global climate change on malaria transmission. (*A*) Uncertainty of the global mean surface temperature increase (with respect to 1990) for the IS92a scenario (*56*); (*B*) uncertainty range of the simulated change in transmission potential of the mosquito population for *P. falciparum*, simulated with the central climate change estimate (expressed in terms of the vectorial capacity); (*C*) uncertainty range for the estimate change in *P. falciparum* prevalence (per thousand) in regions of low endemicity; (*D*) cumulated uncertainty range of the vectorial capacity change, taking into account the uncertainties of both the climate (*A*) and mosquito (*B*) simulations; (*E*) cumulated uncertainty range of the change in prevalence, taking into account the uncertainties of both the mosquito (*B*) and prevalence (*C*) simulations; (*F*) cumulated uncertainty range of the change in malaria prevalence, taking into account the uncertainties of the climate (*A*), the mosquito (*B*), and the prevalence (*C*) simulations.

involves limitations such as simplifications, summarizations, and averaging. This is true for conventional epidemiology, and it is no surprise that ecoepidemiologically based modeling involves similar limitations. Another difficulty with an ecoepidemiologic modeling approach is that vulnerability to global environmental changes varies greatly among different segments of the world's population. Poorly resourced populations such as those of Bangladesh and sub-Saharan Africa will be more vulnerable to adverse climatic events than rich nations. Globally aggregated models average over all populations, but specific projections often are required for more localized populations.

A final point indicated from the previous discussions is that even without climate change and ozone depletion the complexity of influences of various factors upon health defies a ready quantitative analysis of net effects. For example, there appears to be a widespread increase in the tempo of new and emerging infectious diseases (*43*), which probably reflects a combination of demographic and environmental (climatic) changes in addition to increases in drug and pesticide resistance (*44*). Rates of disease and deaths from cigarette smoking are likely to increase in many countries (*45*), and rates of chronic noninfectious disease, especially heart disease, diabetes, and certain cancers, in rapidly developing countries are increasing (*46*). This complex balance sheet makes it difficult to estimate the net impact of climate change and ozone depletion on human population health.

As the full complexity of assessing the health impacts of climate change and ozone depletion cannot be satisfactorily reduced to mathematical modeling, one must question the role of such modeling. Despite the difficulties and limitations of the modeling process, the models discussed previously do draw attention to the possibility of foreseeable health impacts from these global environmental changes. They also indicate the relative importance of climate change and ozone depletion as an influence upon these outcomes, which might enhance public discussion, education, and policy making. However, even more important is the role of ecoepidemiologic modeling in the systematic linkage of multiple cause-and-effect relationships based on available scientific knowledge and reasoned guesses. This would increase our understanding of climate- and UV-related health impacts and identify key gaps in data and knowledge needed to improve analysis of these effects.

Future Research Directions

Planning for the protection of human health from the potential impacts of global climate change and increasing UV radiation as a result of ozone depletion requires a greatly improved understanding of the disease-inducing mechanisms involved, possible synergetic effects, and the vulnerability of populations. An important aspect would be the development of theoretical and conceptual methods for the assessment of the health impact of global environmental changes. Current mainstream epidemiologic research methods are not always suited to adequately addressing health impacts that arise within a systems-based context, namely, a context in which the ecologic and other biophysical processes display nonlinear and feedback-dependent relationships. Consequently, new scientific techniques will be needed, including a substantial reliance on mathematical models.

Development of multidisciplinary, integrated assessment models such as those discussed in this paper therefore must be continued. Much of the modeling of human health impacts will require superimposition of data on, for example, disease incidence, vector populations, demographics, and climate, with linkage to specific geographic locations. Geographic information systems, which are computerized mapping systems,

can assist in the organization and analysis of climate, environment, and disease data. Remotely sensed data from satellite imagery would be especially useful in areas for which data on population distribution, land use patterns, or transportation patterns are unavailable (*16*). For example, satellite-generated habitat maps have been used to project the regional risk of African sleeping sickness, which is carried by tsetse flies (*47*). Data derived from such systems should be integrated at an early stage into the development of integrated mathematical models.

It will be essential to integrate modeling experiments with the monitoring of environmental health indicators. For example, in the sensitive areas bordering endemic regions, enhanced surveillance and response would be an essential step in recognizing and thereby mitigating the emergence of the vector-borne diseases considered, whether caused by climatic changes, resistance development, or other factors. Attention should be directed toward sentinel diagnostic centers in these sensitive areas not only to provide an early warning system but also to improve our knowledge of climate-related diseases and to facilitate improvement of current models. To enhance our understanding of the effects of ozone depletion on skin cancer rates and also on cataracts and immune suppression, it is important to improve the monitoring of ozone trends and UV ground-level radiation as well as skin cancer incidence over a range of latitudes. This would improve our risk assessment and probably reduce the large number of uncertainties surrounding the estimates.

Of course, continued epidemiologic research would be necessary to improve our understanding of global environmental change–human health relationships. Examples of such research questions, related to the subjects described in this paper, include: What empirical evidence is there of indirect climatic influences on changes in vector-borne diseases? What is the role of acclimatisation (whether natural or technical) in the assessment of the balance between heat-related and cold-related deaths in different geographic and population settings? What is the precise relationship between UV radiation and MSC, i.e., what wavelengths are most effective and at which stage of tumor development? Other important topics include further analysis of the impact of increased UV-B levels on immune functioning and disease incidence, determination of the dose–response relationship between UV-B and cataracts, and an assessment of how levels of malnourishment, immunosuppression, and infectious diseases interact. Empirical epidemiologic studies of recent climate/health relationships in areas where regional climate change has occurred (for whatever reason), as a partial analogue of future climate change impacts could assist in revealing some of the relationships mentioned above.

Finally, in the health impact assessment of global environmental changes, taxonomy of the systems under consideration is likely to change during the often prolonged periods of simulation. Living organisms such as human beings, animals, ecosystems, and societies can respond, react, learn, adapt, and influence each other. Development of resistance by various disease-causing parasites to the drugs used in treatment is an examples of a system adapting to a changing environment. Therefore, assessing the future of systems for the next decades without considering the ability of the systems to adapt to changes may generate a misleading picture of the impacts of these changes. In recent decades, new computer-based modeling tools have been developed that enable these complex adaptive systems to be studied. Such tools include genetic algorithms, cellular automata, artificial life forms, and nonlinear dynamic systems. The use of these tools, which simulate evolutionary processes such as learning and adaptation and that include continuous changing of the underlying systems, may be essential in the future assessment of the impact of global change (*14,48*).

Conclusion

The scientific and policy community have been slow to recognize the potential importance and scope of human health impacts of global environmental changes, and only little scientific literature on the subject has been generated to date. Given the many uncertainties in health impact assessment and the complexity of the processes involved, many assessments have been qualitative or semiquantitative. Although epidemiology is the basic quantitative science of public health, only for a few of the expected impacts of climate change and ozone depletion such as mortality due to thermal stress is an extension of the standard epidemiologic risk assessment possible. For other impacts, new modeling techniques are required. However, construction of integrated models for the health impact assessment of global environmental changes is still a relatively new science. Therefore, the first-generation models briefly presented in this paper are meant to increase our insights in the underlying processes of climate change, ozone depletion, and human health, and intended to stimulate and contribute to ongoing discussion on the development of methods in the analysis of the interactions among environmental changes, ecosystems, and human health.

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